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Analysis of energy management for heating, ventilating and air-conditioning systems

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EER;
VRV

Abstract In the office buildings, large energy is consumed due to poor thermal performance and low efficiencies of HVAC systems. A cooling load calculation is a basis for the design of building cooling systems. The current design methods are usually based on deterministic cooling loads, which are obtained by using design parameters. However, these parameters contain uncertainties, and they will be different from that used in the design calculation when the cooling system is put in use. The actual cooling load profile will deviate from that predicted in design. A modified bin method was used in this paper to optimize the energy efficiency ratio (EER). A design optimization method is proposed by considering uncertainties related to the cooling load calculation. Impacts caused by the uncertainties of seven factors are considered, including the outdoor weather conditions and internal heat sources. The cooling load distribution is analyzed. Comparison between the modified bin method and CLTD/SCL/CLF method is also conducted. With the distributions of their energy consumption, decision makers can select the optimal configuration based on quantified confidence. According to the economic benefits and energy efficiency ratio, using modified bin method will increase the overall energy efficiency ratio by 45.57%.

1. Introduction

Energy is a vital factor for the success of all economies in the immediate and long-term future. Since the energy crisis of 1970 s, people needed to determine how much energy buildings were using and to identify how that energy use could be reduced. This would have direct effects on building designers, managers, and owners. As a result, Building Energy Analysis (BEA) is becoming an important tool in the HVAC design field. BEA is the technique of estimating energy use and operating costs for building and its energy consuming systems. A wide variety of building energy analysis methods are currently available to HVAC engineers and range from simple to sophisticated one. The simplest methods involve the largest number of simplifying assumptions and, therefore, tend to be the least accurate. The most sophisticated methods involve the fewest assumptions and thus can provide the most accurate results. In selecting the procedure to be used for a specific project, it is important that the limitations of the procedure be recognized. Modified Bin Method is one of the most energy analysis methods used. It estimates both heating and cooling loads, using instantaneous energy calculation at many different outdoor dry bulb temperature conditions, and multiplying the results by the number of hours of the occurrence of each

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Nomenclature

A	area (m^2)
c_p	specific heat at constant pressure (J/kg K)
ESTD	temperature difference (°C)
FPS	fraction of possible sunshine
h_{fg}	evaporation heat energy (J/kg)
q^o	heat energy per unit of floor area (W/m^2)
SC_i	shading coefficient of fenestration component of exposure (i)
T	temperature (°C)
TSCL	total solar cooling load (W/m^2)
U	heat transfer coefficient ($W/(m^2\,K)$)
V^o	volume flow rate (m^3/s)

Greek symbols

ρ	density
ω	humidity ratio of the air (kg_w/kg_a)

Subscripts

a	air
c	conduction
eq	equipment
i	orientation number
inf	infiltration
L	lighting
lat	latent
o	outside
occ	occupancy
r	room
s	sensible
sg	solar glass
sw	solar wall

Abbreviations

AHU	air handling unit
AU	average usage during the occupied or unoccupied time periods
COP	coefficient of performance
dbt	dry bulb temperature
DX	direct expansion
EER	energy efficiency ratio
Eff	efficiency
HVAC	heating ventilation and air conditioning
PLF	partial load fraction
VRV	variable-refrigerant-volume

condition. This procedure accounts for the part load performance of HVAC equipment and coefficient of performance of the HVAC system. The calculations are performed monthly or annually, and for occupied and unoccupied building hours. Thus, several hundred calculations are used to characterize building energy consumption, rather than 8760 h.

Many contributions have been made in the research to improve the modified bin method to obtain more accurate results and decrease the errors and the defects of this method in order to get more precise results and increase the performance of the calculations. One of the first developments in energy calculation is done by Fazli et al. [1]. They performed 780 annual building energy simulations using BEopt and Energy Plus to predict the energy and cost impacts of realistic excess static pressures for typical new and existing single-family homes with both permanent split capacitor (PSC) blowers and electronically commutated motors (ECM) in 15 U.S. climate zones. Garnier et al. [2] modeled a real non-residential building located in Perpignan using the Energy Plus software. They used the predicted mean vote (PMV) index as a thermal comfort indicator and developed low-order ANN-based models to be used as controller's internal models. A genetic algorithm allowed the optimization problem to be solved. Also they compared the proposed management strategy with basic scheduling techniques. The factors that affect the adoption behavior for residential Heating, Ventilating, and Air Conditioning (HVAC) systems were identified by Noonan et al. [3]. Their study included a spatial and temporal contagion effect, house characteristics, and other economic and contextual factors. Reductions in HVAC (heating, ventilation and air conditioning) energy consumption can be achieved by limiting heating in the winter or cooling in the summer. However, the resulting low thermal comfort of building occupants may lead to an override of the HVAC control, which revokes its original purpose. This has led to an increased interest in modeling and real-time tracking of location, activity, and thermal comfort of building occupants for HVAC energy management. To measure physical activity, Rana et al. [4] developed an activity classifier, which achieves 10% higher accuracy compared to Support Vector Machine and k-Nearest Neighbor. A multilayer perceptron ensemble was selected by Wei et al. [5] to build the total energy model integrating three indoor air quality models, the facility temperature model, the facility relative humidity model, and the facility CO_2 concentration model. To balance the energy consumption and the indoor air quality, a quad-objective optimization problem was constructed. The problem was solved with a modified particle swarm optimization algorithm producing control settings of supply air temperature and static pressure of the air handling unit. Kusuda [6] work included a comparison between the modified bin method and different simulation programs (ECUBE, EASA, BLDSIM, BLAST, DOE-2, AXCESS, and TRACE). This comparison showed a similarity in the results if the simulation is done by the same user. Also Kusuda et al. [7] established the load as a function of outside dry bulb temperature by using the diversified loads rather than peak loads. The modified bin method was extended by Knebel [8] to calculate weekday/weekend and partial-day occupancy effects. To enhance the primary and secondary equipment performance, the building load was calculated at two temperatures (peak cooling T_{pc} and peak heating T_{ph}). Moreover, the advantages and disadvantages of using modified bin method were provided by Knebel and Silver [9]. In another hand, a methodology for retrofit Canadian office buildings and screening energy efficiency was developed by Chidiac et al. [10]. Vadon [11] developed a linear equation between the outside air temperature and solar insolation. In addition, Claridge et al. [12] compared the performance of hourly simulation program DOE-2 and improved modified bin procedure for different cases in each of four seasons. The results of 80% of the cases examined were better when modified bin method was used. In order to enhance energy performance of retrofit buildings, EER strategies were developed [13]. A lot of the researches showed that EER could have great achievements if it is correctly achieved. To choose the suitable technologies, an optimization process with a comprehensive consideration of the economic benefits and the energy efficiency must be done [14]. The crucial role in optimizing the air-conditioning system in retrofit buildings was proposed by Ding et al. [15]. It is played in emission reduction and energy efficiency improvement.

2. Scope and objective

Unlike the previous studies, this paper presents a method for a deep building air conditioning system design based on the whole building's thermal analysis with cooling demand reduction, in particular, focus. This work was set against recommended practice office building energy benchmarks in Egypt, and following a comprehensive building audit. The scope of this study aimed to study the modified bin method usage and performance in calculating the cooling and heating loads, the cooling and heating energy, the energy cost, the coefficient of performance and EER. Also, a comparison is made between the modified bin method and CLTD/CLF/SCL method by calculating the energy consumption of each method and determining the best method with combined consideration of feasibility and the building energy efficiency.

3. Cooling load calculations using modified bin method

The modified bin method establishes the load as a function of outdoor dry-bulb temperature. Moreover, it includes HVAC distribution system and plant equipment effects (capacity and efficiency) in energy calculations. In this method, average solar gain profiles, average equipment and lighting profiles and cooling load temperature difference values are used to characterize the time-dependent load. Time dependencies resulting from scheduling are averaged either over a selected period or over multiple calculations. Normally, two calculation periods, representing occupied and unoccupied hours, are sufficient, although any number can be used.

The components of the load profile are as follows:

- Solar gain through the glass.
- Solar gain through walls and roof.
- Conduction gains through the glass, walls, and roof.
- Lights.
- People.
- Equipment.
- Infiltration.

All loads will be expressed as W/m^2 of building conditioned floor area.

3.1. Solar gain through the glass

Solar gain through glass often represents a major cooling load and is highly variable with time and orientation.

The average solar load component for glass is computed with the following:

$$\dot{q}_{sg} = \sum_{1}^{n} (\mathrm{TSCL}_i) \times A_i \times \mathrm{SC_i} \times \mathrm{FPS}/\mathrm{A}_{floor} \tag{1}$$

where

$$\mathrm{TSCL}_i = \sum_{j=1}^{24} (\mathrm{SCL}_j) \tag{2}$$

In the above equation, the total solar cooling load is calculated by making a summation of all the values of the solar cooling loads for the 24 solar hours.

The fraction of possible sunshine (FPS) is calculated for August and January by the following:

$$\mathrm{FPS} = \frac{\text{Average monthly sun hours}}{\text{Number of days for the selected month} \times \text{Maximum number of sun shine hours}} \tag{3}$$

For each zone, the solar contribution for the glass is calculated in August and January. For the approximation of the seasonal variation of the solar load, a linear relationship of the solar load with outside air temperature is assumed. The linear relationship for the solar gain through glass is derived by calculating the solar load for August and January and then by using the outdoor design temperatures for the summer and winter seasons; two linear equations can be formed in the form:

$$\dot{q}_{sg} = aT_o + b \tag{4}$$

where a, b are two constants.

By solving the two linear equations, the values of the two constants (a, b) are calculated, and the linear relationship of the solar gain through glass can be derived as a function of the outdoor temperature.

3.2. Solar gain through walls and roof

Walls and roofs of buildings consist of various layers of materials, and the structure and operating conditions of the walls and the roofs may differ significantly from one building to another.

The average solar load component for a wall or roof is computed with the following:

$$\dot{q_{sw}} = U_i \times A_i \times \overline{\mathrm{ESTD}}_i \times \mathrm{FPS}/A_{floor} \quad (5)$$

The linear relationship for the solar gain through walls and roof can be formed in the form:

$$\dot{q_{sw}} = aT_o + b \quad (6)$$

where a, b are two constants and can be calculated so the solar gain through walls and roof can be written as a function of the outdoor temperature.

3.3. Transmission gain through the glass, walls and roof

Transmission is the process of transferring heat through a solid, such as a wall, roof, floor, ceiling, window, or skylight. It occurs due to the temperature difference between the outside surface temperature and inside temperature of a wall or roof or window.

The conduction component is computed with the following:

$$\dot{q_c} = U_i \times A_i \times (T_o - T_r)/A_{floor} \quad (7)$$

3.4. Lights

Some of the energy emitted by the lights are in the form of radiation that is absorbed in space and transferred later to the air by convection and the other portion of the energy from lights is in the form of convective heat, which is picked up instantaneously by the air-conditioning apparatus. Under actual operating conditions, the total installed lighting may not be operated continuously during the occupied period. This will tend to reduce the average heat gains so it may be necessary to plot the lighting schedule to find a realistic average. The light component is computed with the following:

$$\dot{q_L} = (\text{Avg. Lighing usage}) \times (\text{Max. Lighting load})/A_{floor} \quad (8)$$

The lighting load is not a function of the outdoor temperature, so it has a constant value.

3.5. Occupancy

Heat given off by people usually constitutes a significant fraction of the sensible and latent heat gain of a building, and may dominate the cooling load in high occupancy buildings such as theaters and concert halls. The latent heat gain is considered as instantaneous because it goes directly into the air in space so this component directly becomes cooling load with no delay. The sensible heat gain from people is not converted directly to the cooling load. The radiant portion is first absorbed by the surroundings and convected to space at a later time, depending on the characteristics of the room and furnishings.

The occupancy component is computed with the following:

$$\dot{q_{occ}} = (\text{Avg. occupancy usage}) \times (\text{Max. occupancy load})/A_{floor} \quad (9)$$

The occupancy load is calculated for the occupied period only. The average usage is obtained for this period. The occupancy load has two components: sensible and latent, which are calculated separately. It is not a function of the outdoor temperature, so it has a constant value.

3.6. Equipment

There are many types of appliances and equipment in restaurants, schools, office buildings, hospitals, and other types of buildings. Heat generated in conditioned spaces by electric appliances such as refrigerator, freezer, TV, computers, printers, and copiers can be significant, and thus, must be considered when determining the cooling load of a building.

The equipment and appliances used in the conditioned space may be sensible or latent loads, and sometimes both. The equipment component is computed with the following:

$$\dot{q_{eq}} = (\text{Avg. equipmen tusage}) \times (\text{Max. equipment load})/A_{floor} \quad (10)$$

And because it has a constant value, so it is not a function of the outdoor temperature.

3.7. Ventilation and Infiltration

The load component due to ventilation or infiltration is a function of the outdoor dry bulb and wet bulb temperatures. This load is calculated for summer and winter and for occupied and unoccupied periods. The sensible component of infiltration is computed with the following:

$$\dot{q_{inf,s}} = \rho_a \times C_p \times V_a^o \times (T_o - T_r)/A_{room} \quad (11)$$

While the latent component of infiltration is computed by the following:

$$\dot{q_{inf,lat}} = \rho_a \times h_{fg} \times V_a^o \times (\omega_o - \omega_r)/A_{room} \quad (12)$$

3.8. Total building loads

The load calculations are performed separately for the occupied (normal operation) and unoccupied (night operation) time periods and then totalized to get the total cooling and heating loads for the occupied and unoccupied periods.

The air-conditioning equipment capacity and power input are expressed as a function of outdoor temperature by selecting two operating capacities and temperatures and then fitting these points to a linear equation. By solving the two equations, the values of the two constants (a, b) are calculated and the linear relationship for the equipment capacity is established. The same procedures are applied to deduce the linear relationship for power input.

Practically all manufacturers' performance data assume full-load steady state operation but in fact, the equipment operates at partial load most of the time so it must be computed. The partial load fraction (PLF) is computed for the occupied and unoccupied periods.

$$\mathrm{PLF} = 1 - D_c \times (1 - \text{Building Load}/\text{Unit Capacity}) \quad (13)$$

The degradation coefficient (D_c) may be specified by the manufacturer or taken as 0.25 as a default value according to the Air-Conditioning and Refrigeration Institute (ARI) in the USA. When the building load exceeds the unit capacity, the PLF is assumed to be 1.0 because the unit will run continuously. The part load can be calculated for day and night periods.

$$\text{Part load} = \mathrm{PLF} \times \text{Cooling or Heating load} \quad (14)$$

The run time for the air conditioning equipment can be estimated for day and night period from the following equations:

$$\text{Day run time} = \text{Day Load} \times \text{Occupied hours}/\text{Capacity} \times \text{Day PLF} \quad (15)$$

$$\text{Night run time} = \text{Night Load} \times \text{Unoccupied hours}/\text{Capacity} \times \text{Night PLF} \quad (16)$$

After calculating the run time of the equipment, it is easy to calculate the cooling and heating energy from the following:

$$\text{Energy} = \text{Power input} \times (\text{Day run time} + \text{Night run time}) \quad (17)$$

The coefficient of performance for the used equipment (COP) is a ratio of heating or cooling provided to electrical energy consumed, and the Energy Efficiency Ratio of the equipment (EER) is the ratio of output cooling energy (in BTU) to input electrical energy (in W h), they both can be calculated easily from the following:

$$\text{COP} = \text{Cooling or Heating Capacity}/\text{Power Input} \quad (18)$$

$$\text{EER} = 3.412 \times \text{COP} \quad (19)$$

4. Case study

An administration building for a University located in Alexandria, Egypt (latitude = 31.2°N and longitude = 29.95°E, at 6.7 m above sea level), was chosen as a case study. It consists of offices and a theater. The building consists of 3 floors with 5 m height and 2326.52 m^2 floor area for each floor. To reduce the cooling and heating requirements, reflective double glazed windows were used. Wall and roof were provided with sufficient insulation to obtain the maximum U-values shown in Table 1. The indoor air conditions shall be 22 ± 1 °C dry bulb temperature in offices and 24 ± 1 °C dry bulb temperature and 50 ± 5% relative humidity in the theater. The philosophy of the HVAC design was based on green building design which recommends Energy conservation, less electrical consumption, and higher reliability. To achieve this aim, the modified bin method, and the CLTD/SCL/CLF method were used in calculating the cooling and heating loads. Based on meteorology data, calculations were made for August and January because they represent the warmest and coldest months of the year.

Owing to the possibility to introduce fresh air to the theater, DX system was regarded as a considerable choice. On the other hand, VRV system was the suitable choice to undertake part of the heating and air-conditioning loads in areas where individual operation is needed. Therefore, two HVAC systems were used. The VRV system consists of 11 air-cooled condensers placed on the roof and 157 indoor units while the DX system consists of 2 air-cooled condensers also in the roof and 2 AHU located above the theater.

Table 1 Heat transfer coefficients.

Building envelop	
U_{wall}	0.4 W/m^2 °C
U_{roof}	0.3 W/m^2 °C
U_{window}	2.8 W/m^2 °C
SC	0.21

5. Results and discussions

5.1. Energy conversation analysis

5.1.1. Analysis of weather data

The day is divided into occupied (day) and unoccupied (night) periods. For each period, the time-dependent loads are averaged and added to the conduction loads such that the load is characterized as a function of outside air temperature for the calculated period. The bin intervals that are measured in six daily 4-h shifts are usually 3 °C [16,17]. The cooling period in Alexandria started from May 1st to October 22nd. Also the occupied period is considered from 7:30 to 18:30. From the meteorological data, the highest outdoor dry bulb temperature is 38 °C and the lowest is 17 °C during the summer period. From the bin weather data, which are shown in Fig. 1, it can be observed that the bin interval (27.5–30.5 °C) represents the highest incidence by 26.14% of the total normal operating time. The maximum value for the bin interval is 36.5-39.5 °C which forms 1.87% of the normal cooling period.

5.1.2. Building load calculation using modified bin method

The schedule of the occupied and unoccupied period is necessary to be known in order to calculate each component of the cooling loads. This schedule can be determined by making a survey of the object building. Tables 2–4 show this schedule for studied buildings. The cooling loads were calculated based on previous equations, and the following linear functions were obtained

$$CL = 3.3176\ T_o + 42.3 \quad (20)$$

Table 5 shows the results of calculating the building loads in each temperature bin. The air conditioning load of the object building is 1175.07 kW while the cooling load per unit area is 168.36 W/m^2.

5.1.3. Building load calculation using CLTD/SCL/CLF method

The CLTD/CLF/SCL calculation method is a manual load calculation method that is based on transfer function method. This method was subjected to several revisions to

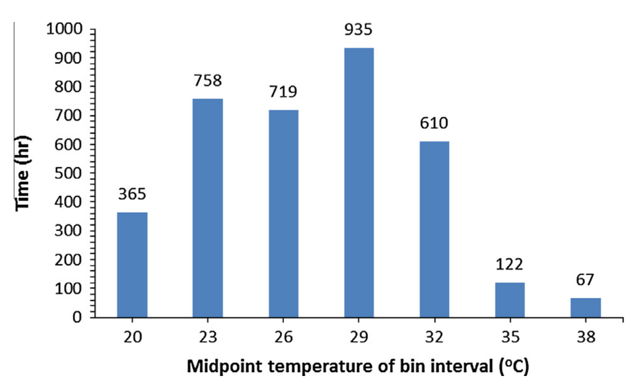

Figure 1 Temperature bin distribution of the normal operation cooling period.

Table 2 Lighting weekly schedule.

Time	12 AM	1 AM	2 AM	3 AM	4 AM	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM
AU	0	0	0	0	0	0	0.3	0.3	0.5	0.5	0.3	0.3
Time	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	7 PM	8 PM	9 PM	10 PM	11 PM
AU	0.3	0.3	0.3	0.3	0.5	0.95	0.95	0.5	0	0	0	0

Table 3 Occupancy weekly schedule.

Time	12 AM	1 AM	2 AM	3 AM	4 AM	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM
AU	0	0	0	0	0	0	0.3	0.3	0.8	0.95	0.95	0.95
Time	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	7 PM	8 PM	9 PM	10 PM	11 PM
AU	0.95	0.7	0.8	0.95	0.95	0.95	0.7	0.3	0	0	0	0

Table 4 Equipment weekly schedule.

Time	12 AM	1 AM	2 AM	3 AM	4 AM	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM
AU	0	0	0	0	0	0	0	0.3	0.8	0.95	0.95	0.95
Time	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	7 PM	8 PM	9 PM	10 PM	11 PM
AU	0.95	0.8	0.7	0.95	0.95	0.95	0.5	0.5	0	0	0	0

Table 5 Cooling load calculations.

Bin interval (°C)	Cooling period (7:30 AM to 6:30 PM)	
	Time (h)	Load (W/m^2)
20	356	108.65
23	758	118.6
26	719	128.55
29	935	138.51
32	610	148.46
35	122	158.41
38	67	168.36

accommodate the problems that rose from approximations and limitations to cover more accurate tabulated data. The CLTD, SCL, and CLF vary with time and are a function of environmental conditions and building parameters. The results of cooling load calculation based on CLTD/SCL/CLF method show that it required cooling load equals 1319.57 kW.

5.2. Energy conservation comparison

The cooling load comparison was made between the results from using modified bin method and CLTD/SCL/CLF method. Fig. 2 shows that the solar gain through glass and infiltration values are near to each other, and the deviation between them equals +8.37% and +5.026% respectively. But the other load deviation is between +17.78% and +34.98%.

Fig. 3 illustrates the expected energy consumption for each interval bin temperature by using Eqs. (13)–(17) when the

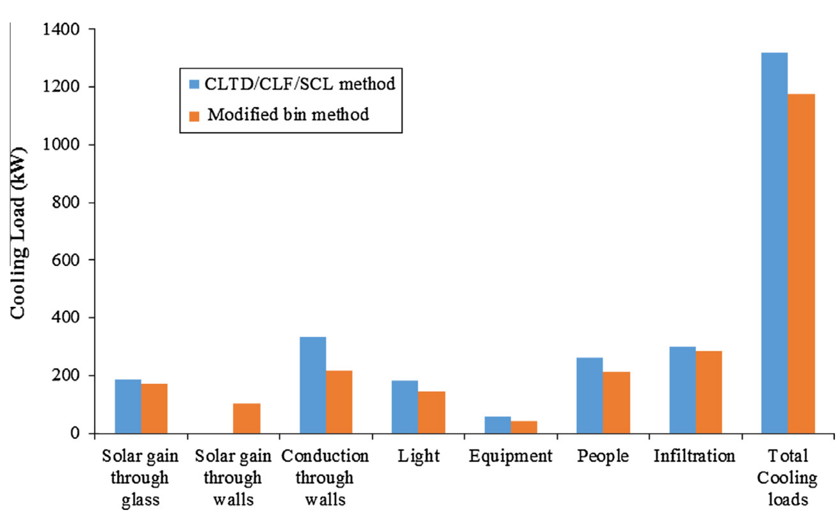

Figure 2 Cooling load comparison.

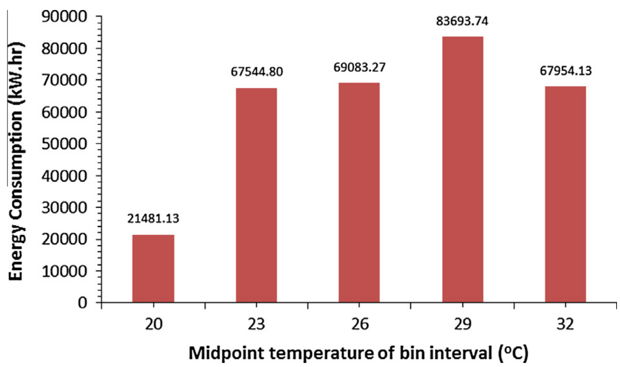

Figure 3 Air-conditioning energy consumption using modified bin method.

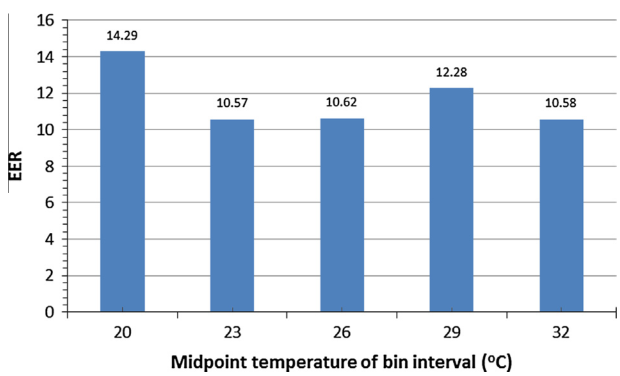

Figure 4 The energy efficiency ratio (EER) vs. temperature bin interval.

energy resource was electricity. From this figure, it can be found that 309757.1 kW h cooling energy will be consumed, and the annual energy per unit area is 133.14 kW h/m^2. The saving cooling energy is 45.57% if modified bin method is used while using CLTD/SCL/CLF will save 33.42%. Fig. 4 illustrates the relation between the energy efficiency ratio (EER) and temperature bin. It can be observed that the EER of modified bin method is ranged between 14.29 and 10.58. These values are higher than EER obtained from using CLTD/SCL/CLF method (10.89).

6. Conclusions

The modified bin method is the major method that was used in this paper to propose and optimize the energy efficiency (EER). A case study was used to ensure the applicability and explain the analysis procedures. The modified bin method results were compared with CLTD/SCL/CLF method results. According to the previous analyses, some important conclusions could be noted down:

- The loads calculated by the modified bin method are represented as a function of the outdoor temperature (a linear function). This makes it easy to study the load change according to the change of the outdoor temperature and make a full prediction, which helps in sizing the proper air conditioning equipment.
- For the practical EER projects, the results obtained from using modified bin method simulation, which are calculated based on dynamic loads, are accurate enough.
- Comparing the modified bin method with the CLTD/CLF/SCL method according to loads, the values of the loads and the error percentage showed that the modified bin method is more accurate and precise.
- The energy saved by using modified bin method is higher than that of using CLTD/CLF/SCL method. Using modified bin method will save energy by 45.57% while the other method will save energy by only 33.42%. The environmental benefits would also be realized with energy conservation benefits in the long run.

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